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RELATIVE LOCATION OF EXPLOSIONS USING SURFACE WAVES

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RELATIVE LOCATION OF EXPLOSIONS USING SURFACE WAVES

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ABSTRACT

A method of relative location for explosions using Rayleigh waves is developed and tested. It involves cross correlating a wavetrain with a previously recorded signal from the same source region and determining a relative "travel-time" from the peak in the cross correlation trace. Locations are fairly accurate, but do not compare with the precision obtained with body waves and relative travel-time corrections. A number of causes of errors are discussed, and it is estimated that a sophisticated application of this method would yield location comparable to relative travel-time locations for large events.

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INTRODUCTION

Location of seismic events is traditionally done by timing the first arrivals of the body-wave phases P, P_n, or P_g, depending on epicentral distance. Even when arrival times of these phases are accurate, location errors of up to 50 kilometers can result because of the heterogeneity of the earth and lack of azimuthal control. Locations using other body-wave arrivals are subject to greater error since the arrival time of any phase after the initial P, P_n, or P_g is obscured by continuing motion. And the use of surface waves to locate entails such problems that no one apparently has used them for this purpose. The primary difficulty is observational in that the surface waves, being dispersed, have no definite arrival time. Given well-recorded signals, group arrival times for particular periods can be assigned as is done for group velocity measurement; however, even with the arrival times well determined, the group travel time must be accurately known from the epicenter to all the recording stations in order to make an accurate location. Rayleigh-wave group velocities will vary between about 3.0 (shields) and 4.0 (oceans) for periods between 20 and 30 seconds, and travel times based on this difference could vary by several hundred seconds for teleseismic distance. On the other hand P-wave travel times are relatively invariant over the whole earth for a given teleseismic distance, and differences between observed arrival times and those predicted by standard P-wave travel-time tables seldom exceed five seconds. Without extremely detailed knowledge of surface-wave velocities over the whole earth, we cannot expect to even approach the worst location errors for first arrivals, that is, about 50 kilometers.

Relative location of explosions using predetermined travel-time anomalies for compressional waves has reduced location error by nearly an order of magnitude in the Nevada and Rat Islands regions as reported by Chiburis (1968) and Chiburis and Ahner (1969). This method of relative location requires a reference event whose exact position is known and a common recording network for this and another event with unknown epicenter in the same region. The accuracy of the epicenter location of the detected event is directly related to its proximity to the reference event. That is, the validity of relative travel times is dependent on the distance between the detected event and the reference event from which the relative travel times were determined because of the changes in compressional-wave travel paths.

An analogous method of relative location using surface waves is possible. Again a reference event with an exactly known location is required. Cross correlation of the reference event's waveform with that of the detected event provides arrival times of surface-wave energy for any period at which there is detectable ground motion. Instead of basing the location of the detected event on estimated travel times over the entire paths to the stations, the location can be made relative to the reference event when travel times to the stations from it are already known and serve to remove most of the travel-time uncertainty associated with surface waves from the detected event. This, coupled with the fact that apparent velocities for P waves are 3 - 8 times larger than surface-wave velocities and therefore introduce more epicenter error per second of arrival-time error (or residual), makes relative location by surface waves attractive. Also, the surface-wave method can use recordings at regional distances whereas the relative travel-time method for body waves must

usually exclude regional data because of its large variation in travel times at a given distance and because of the uncertainty in associating a first arrival with one of several different branches in the travel-time curves. The accuracy of the location of the detected event will again depend on its distance from the reference event since travel paths to the recording network are proportionately changed. Moreover, a knowledge of phase velocities in the source region is desirable; but in the case of assumed velocities, location accuracy is not severely affected, as will be discussed later. If a degree of accuracy comparable to that obtained using relative travel times with body-wave location is desired, the surface-wave location method appears feasible only for explosions. This is because the initial-phase radiation patterns for two earthquakes, even in the same region, cannot be assumed to be identical. Furthermore, a distance in source depth alone will alter the recorded wave train. However, for some earthquakes P arrivals are emergent and thus arrival times are uncertain or for some others only the surface waves are detected at all; in these cases a location using surface waves would be the only obtainable one.

SURFACE-WAVE RELATIVE LOCATION METHODS

Matched filter location

With the latitude and longitude of a reference event known precisely and its origin time known only approximately, the latitude and longitude of a detected event in the same region can be determined along with an estimate of its origin time. The accuracy of the origin time will reflect the error in the approximated reference event origin time. The mathematical method is analogous to body-wave location algorithms and is as follows. For each station, Rayleigh-wave signals will be recorded for both events as shown in Figure 1. A procedure using visual analysis to pick the times of arrival of corresponding wave groups of the same period as is done in group velocity determination would provide the necessary data to locate the detected event. However, low signal-to-noise ratios and dispersion of the second signal relative to the reference one may cause inaccuracies in this approach. Alexander and Rabenstine (1967) have used reference event signals to detect signals from other events in the same region by cross correlation. This method of filtering is applicable to surface-wave location. The peak in the cross correlation trace in Figure 1 indicates the time of overlap of the two signals as received at a given station. If the reference-signal time window is chosen to begin with the group arrivals of maximum velocity and to end with the groups of minimum velocity and if the time window of the detected event's signal is made longer by the inclusion of some noise in front, the cross correlation trace will peak at some time increment τ (Figure 1) relative to the start, t'_p, of the detected event's window such that the "time of arrival" of the new

signal can be determined accurately. We form then equations of "travel time" for the two signals at any station:

$$TT_r = t_r - O_r$$

$$TT_p = t'_p + \tau - O_p = t_p - O_p$$

where subscripts r and p refer to the reference event and detected event respectively, t_r and t_p refer to corresponding arrival times, and O_r and O_p are the approximated origin times. An approximate O_r is sufficient since errors in O_r will be reflected almost entirely in errors in the origin time and not in the location of the detected event. (Note that by adding a constant to both travel time equations, the time of any particular group arrival could be represented; this would be accomplished by moving t_r forward in time in Figure 1.) A residual equation for each station can then be written

$$E = (t_p - O_p) - (t_r - O_r) \qquad (1)$$

This expresses the differences in travel times and can be related to errors in the initial assumptions of latitude, longitude, and origin time for the detected event as in body-wave algorithms for location thus:

$$E = \frac{d(TT)}{dR} \cos\alpha \; dY_p + \frac{d(TT)}{dR} \sin\alpha \; dX_p + dO_p \qquad (2)$$

where α is the epicenter-station azimuth; $\frac{d(TT)}{dR}$ is the change in travel time due to a change in epicentral distance R (in kilometers); and dY_p, dX_p, dO_p are the corrections to be applied to the initial assumptions of latitude, longitude, and origin

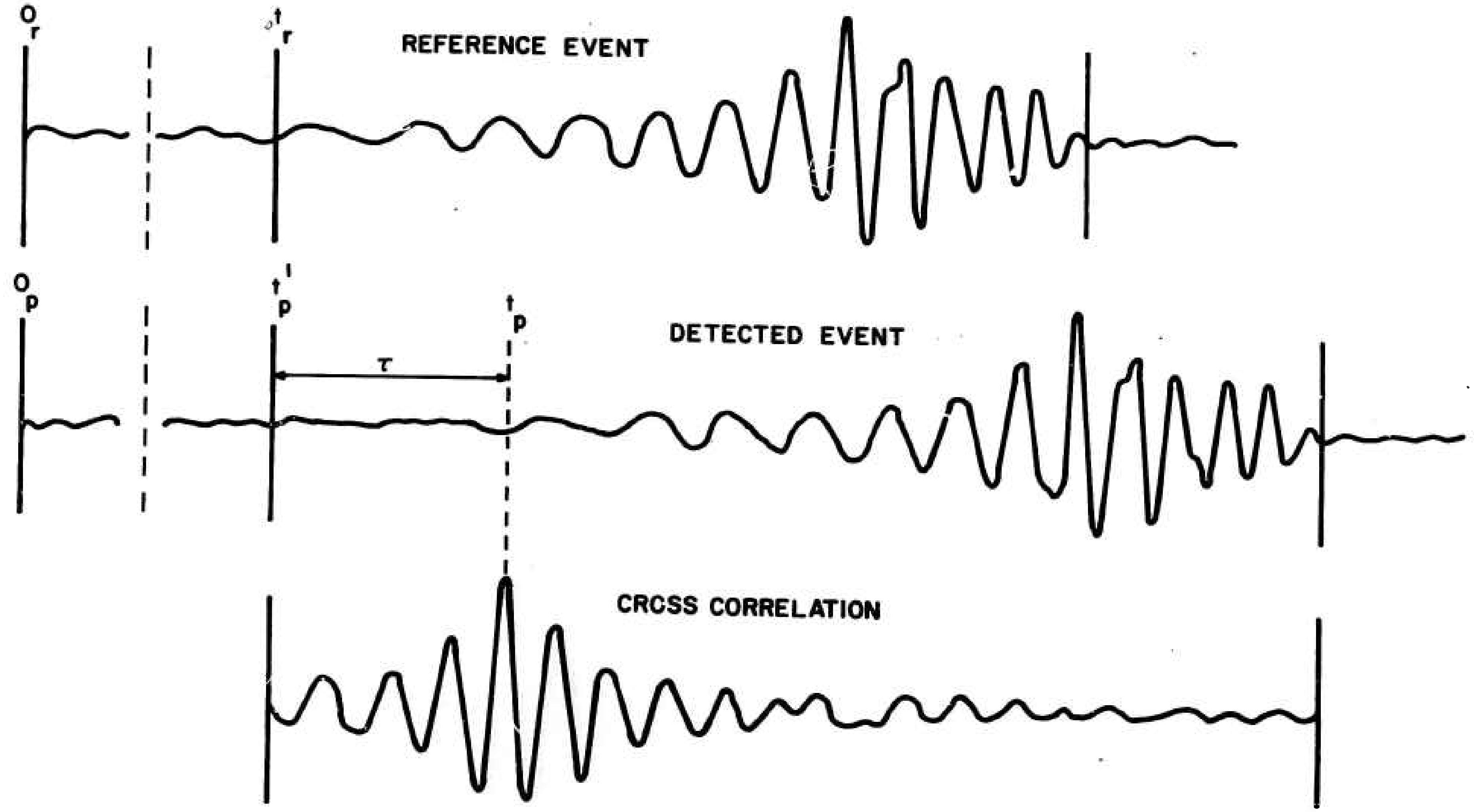

Figure 1. Use of matched filter to determine a relative arrival time for Rayleigh waves from a detected event.

time, respectively, of the detected event. Since we will be locating events which are less than 200 km from the reference events in this study, the flat earth approximation which substitutes kilometers for degree increments of longitude and latitude contributes less than 0.1 km to location error and is therefore acceptable. The value $\frac{d(TT)}{dR}$ is simply the inverse of phase velocity C. It is intuitive that the selected phase velocity for use in the location should correspond to periods which show the maximum amplitudes on the recordings of the two events since for a given station the peak in the cross correlation trace should "move out" with this velocity when the signals originating from a fixed source are correlated with signals from another source moved successively greater distances from the fixed source and dispersion changes the waveforms slightly each time. This "move-out" will be investigated later with synthetic seismograms. So (2) can be written as

$$E = (\cos\alpha/C)\ dY + (\sin\alpha/C)\ dX + dO \tag{3}$$

Similar equations of condition can be written for each recording station and the solutions dY, dX, dO are obtained by use of the least-squares normal equations.

An iterative process can be employed as in body-wave location algorithms. First rewrite (1) as

$$E = t_p - t_p^c$$

where $t_p^c = O_p + t_r - O_r$ is the computed arrival time in the first iteration. After the first solution is obtained, the travel times from the reference event will still be used and the predicted arrival time at any station in subsequent

iterations will be

$$t_p^c = 0_p + t_r - 0_r + (R_p - R_r)/C$$

where R_p and R_r are the distances to the station from the location given by the previous iteration and from the reference event, respectively; and 0_p is the origin time given by the previous iteration. Thus, arrival time at the station is computed assuming the velocity C of the maximum amplitudes in the wave train and using the known travel times from the reference event.

Dispersion effects

If the detected event is displaced from the reference event, dispersion will perturb its wave train relative to that of the reference event at each station. We will demonstrate empirically that the move-out velocity of the correlation peak is approximately identical to the phase velocity of the maximum recorded amplitudes of the wave train when a signal is cross correlated with dispersed modifications of itself. The dispersed signals were generated from actual recorded signals using reported phase velocities and the synthesis procedure described by Sato (1960). Two structures were used: 1) "Shield", for which the average phase velocities shown by Brune (1969) were adopted and 2) "Basin-Range", for which the theoretical phase velocity curve of Smith (1962) for the "Nevada Region" was adopted.

Dispersed signals were generated every 30 km out to 150 km as though the epicenter was moved these distances successively away from the recording station. An example of the dispersed signals is shown in Figure 2 for the actual FAULTLESS recording

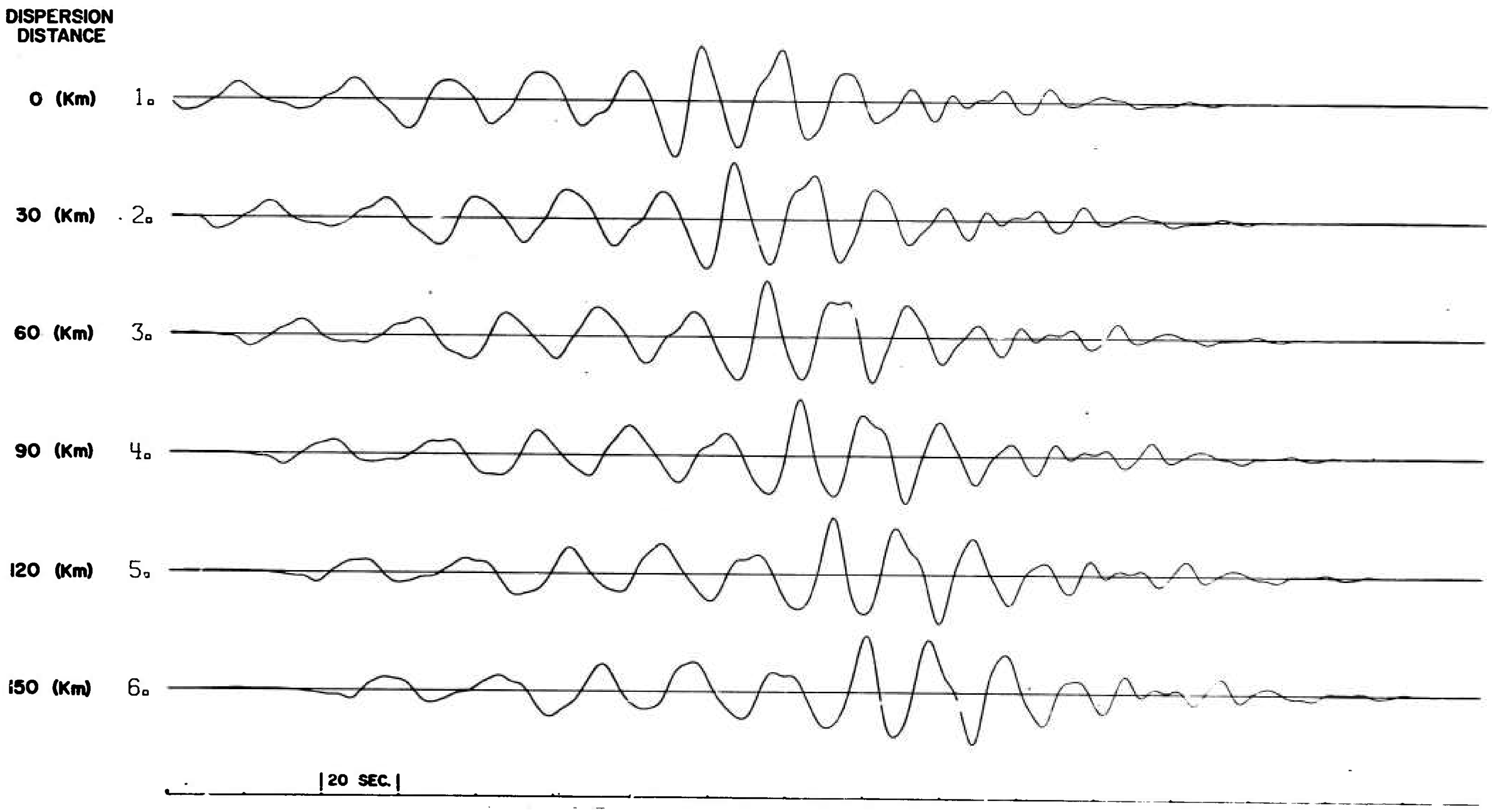

Figure 2. Dispersed modifications of the FAULTLESS recording at NP-NT using "SHIELD" dispersion.

at NP-NT. Figure 3 shows the traces produced by correlating the actual FAULTLESS recording with its Shield-dispersed modifications as well as with itself. (The original signal was displaced 34 seconds backward in time before commencing correlation with the traces of Figure 2.) The move-out measured on the cross correlation peak in Figure 3 is 3.66 km/sec which is very close to the 3.61 km/sec phase velocity for a period of 18 seconds in the "Shield" dispersion curve of Brune. Eighteen seconds is approximately the period of maximum recorded amplitudes for the signal received at NP-NT from FAULTLESS. Figure 4 shows two other signals, FAULTLESS as recorded at RK-ON and MILROW at HN-ME, which were utilized just as FAULTLESS at NP-NT was used to determine move-outs. These same three signals were also subjected to "Basin-Range" dispersion. The results for all six move-out tests are given in Table I; note that the three signals together span a large epicentral distance range. Measured move-out velocities do not differ from the phase velocity for the periods of the maximum recorded amplitudes by more than .06 km/sec. Thus, in our surface-wave location, we use the assumed (or hopefully determined) phase velocity of the maximum recorded amplitudes. This phase velocity is valid for the structure between the epicenters if they are on nearly a great circle path with the station since the dispersion of one event signal relative to the other would be mostly controlled by the structure between epicenters. If the circle path through the epicenters were normal to the epicenter-station azimuth, the two travel paths to the station would not be coincident at anytime, and the dispersion of one signal relative to the other would be controlled by differences in structure along the whole travel paths.

Note that in Figure 3 no apparent deviation from a constant move-out of the peak occurs, and we would expect the move-out to

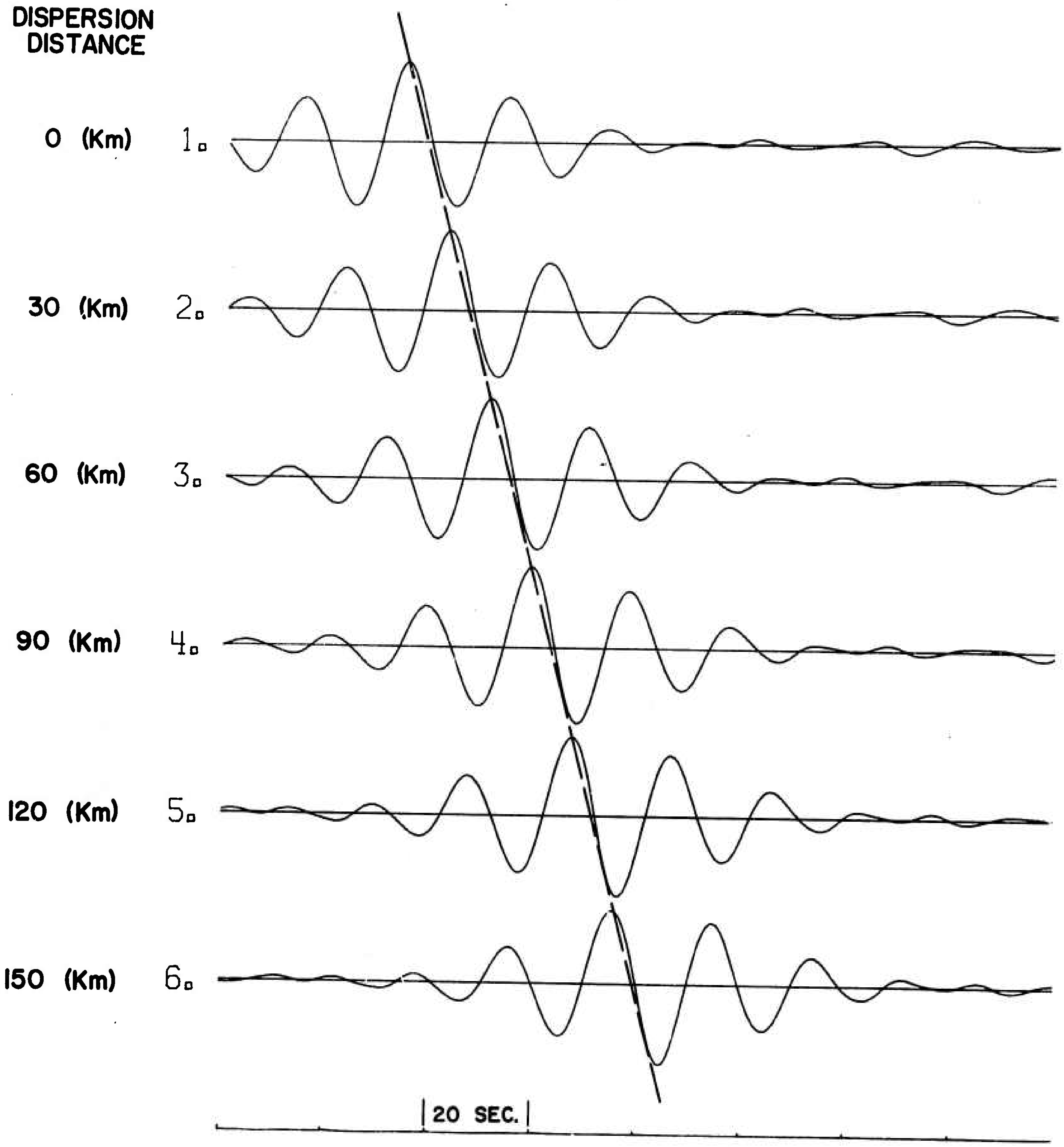

Figure 3. Correlation of the actual FAULTLESS recording at NP-NT with its dispersed modifications.

TABLE I

Cross Correlation Peak Move-Out for Various Synthetic Cases

SOURCE OF ACTUAL RECORDING

EVENT	STATION	DISTANCE	APPROX. PERIOD OF MAXIMUM RECORDED AMPLITUDES	STRUCTURE USED IN SYNTHESIS	PHASE VELOCITY FOR PERIOD OF MAX. AMPLITUDE	OBSERVED MOVE-OUT
FAULTLESS	RK-ON	2228	14 sec	Shield	3.45	3.41
				Basin-Range	3.21	3.17
FAULTLESS	NP-NT	4197	18 sec	Shield	3.61	3.66
				Basin-Range	3.34	3.38
MILROW	HN-ME	7444	20 sec	Shield	3.68	3.64
				Basin-Range	3.39	3.33

continue at the same rate if signals were synthesized for sources farther removed. However, in locating detected events which are distant from the reference event, there is a limiting factor (Figure 3) which is the increase in amplitude of a peak adjacent to the desired peak. In this case choice of a false correlation time is possible. Signal-to-noise ratios less than those used in this study would also lead to wrong choices. We estimate that events no more than 200 km from the reference event could be located when signal-to-noise ratios were high. Poor signal-to-noise ratios may diminish this range drastically.

Phase velocity and location accuracy

In determining the detected event's location the computed distance in kilometers from the reference epicenter is dependent upon the phase velocity chosen. If, for instance, all recording stations had maximum amplitudes at about the same period and if the estimated phase velocity for this period in a certain structure was 3.40 km/sec, the error in the computed epicenter of the detected event would be about 2.6 km when it was in fact 50 km from the reference epicenter and when the true phase velocity in the source region were 5 per cent lower than the assumed 3.40 km/sec. Similarly, an epicenter 100 or 200 km away from the reference epicenter would be mislocated by only 5.2 or 10.0 km, respectively, for a 5 per cent error in phase velocity. Examination of the curves of Brune and Smith reveals that it would be difficult to assume a phase velocity corresponding to periods in the range of 10 to 30 seconds which was more than 5 per cent different from the actual value for a continental region. At a period of ten seconds, the range in phase velocity over the four widely-varying continental structures of Shield, Basin-Range,

Mid-Continent, and Alpine (using Brune's terminology) is only from 3.12 to 3.35 km/sec. At a period of twenty seconds, the corresponding range is 3.37 to 3.68, and for a period of thirty seconds is 3.62 to 3.92. Thus, taking a value midway in the ranges and allowing for small errors in period read from the recordings, we can minimize errors in assumed phase velocity to less than 5 percent even when no information on the structure of the source area is available. As a result, we would expect location bias due to these errors to be no more than mentioned above. We should point out, however, that problems could arise when possible paths to a station from the detected event lay close to continental-oceanic boundaries.

Location using phase differences

The problems associated with dispersion of one signal relative to another can be circumvented by Fourier analyzing the cross correlation of the two signals. It has been shown that the cross correlation of the signals at two stations which are in line with a given event represents the medium response to an impulsive point source applied at one station and received at the other (Landisman et al, 1969). Analogously, the medium response between two events is represented by the cross correlation of their signals received at a given station when the events are aligned with the station. Whenever the epicenters are not aligned with the station, the medium response represented by the cross correlation refers more to differences in structure along the entire travel paths. Fourier analysis of the cross correlation trace determines arrival times versus frequency such that τ and t_p in Figure 1 are both frequency-dependent. Thus (1) should be rewritten

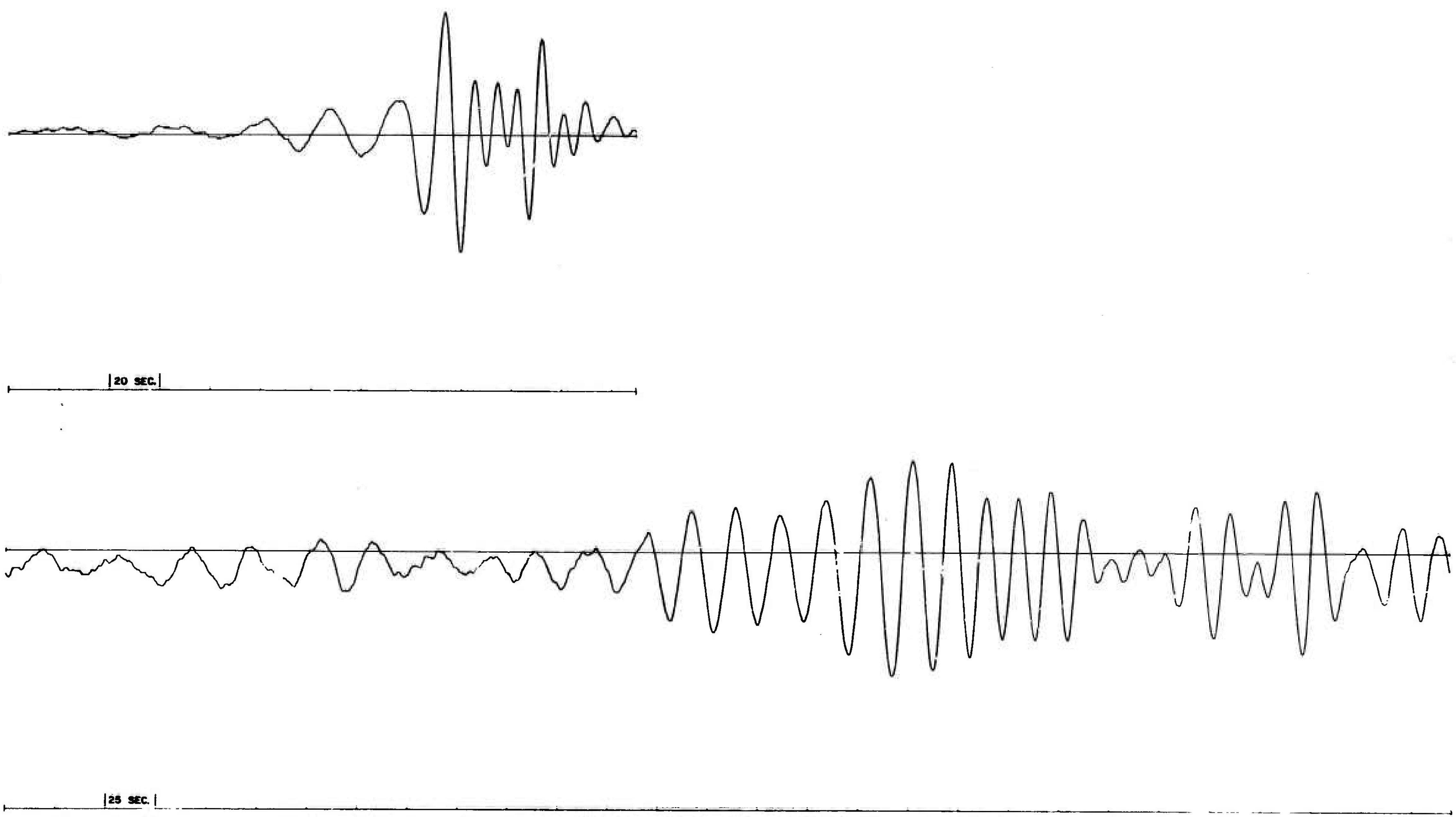

Figure 4. Actual recordings of FAULTLESS at RK-ON (top) and MILROW at HN-ME (bottom).

as:

$$E(f) = [t_p(f) - O_p] - [t_r(f) - O_r]$$

to incorporate the information available from the entire spectrum. Also (3) should be expressed as

$$E(f) = [\cos\alpha / C(f)]\ dY + [\sin\alpha / C(f)]\ dX + dO$$

It is clear that phase velocities should be used since the Fourier analysis of the cross correlation determines the time difference in phase peaks between the windowed signals of the reference event and the detected event. The number of conditional equations used in the location is now multiplied by a factor equal to the number of frequencies used. The information from the received signals used in the location is more complete and precise than in the simple method of picking the correlation peak time. Again, the accuracy of the location depends on how well the surface-wave velocities are known. Also, only frequencies in a band over which the phase differences remain smooth should be used; this limitation will undoubtedly alter the exact band of frequencies used at each station for a given location.

RESULTS

Recordings of the JORUM, JORUM collapse, BOXCAR, FAULTLESS, MILROW, and LONG SHOT Rayleigh waves digitizated at four or five points per second for the stations indicated in Table II were already available for the most part. Cross correlation traces were formed by multiplying the individual spectra in the frequency domain and inverse transforming. The proper peaks in the cross correlation traces were readily apparent in most cases because of the high signal-to-noise ratios. Although LONG SHOT was barely detectable at some of the stations, the strength and duration of the MILROW signals (about one order of magnitude larger) caused the cross correlation traces to peak at the proper times. Relative locations for the event pairs shown in Table II were computed, and the vectors from the true locations to the computed relative locations are also given in Table II under the column headed "matched filter". As a comparison, the error vectors for traditional compressional-wave locations and relative travel-time locations are given for the same events under the columns headed "body waves" and "relative travel times", respectively. Depth was restrained to zero, the true origin times of the reference events were used, and the Herrin 1968 travel-time tables were employed in all cases. Relative travel times were determined from the reference events in the manner shown by Chiburis (1968). The JORUM-BOXCAR and FAULTLESS-BOXCAR pair were processed with and without LC-NM, the only station at regional distance, because of the known deleterious effect of regional stations on body-wave and relative travel-time locations. Results in Table II clearly show this. However, the matched filter location is considerably improved by the addition of this station in both cases, due mainly to the increased azimuth aperture of the stations about the epicenter.

TABLE II

Comparison of Location Methods

REFERENCE EVENT	LOCATED EVENT	DIST. FROM REF. EVENT	STATIONS USED	ERROR VECTORS FROM TRUE TO COMPUTED LOCATION		
				BODY WAVES	RELATIVE TRAVEL TIMES	MATCHED FILTER
JORUM	JORUM COLLAPSE	0km, 0°	PG-BC, RK-ON, WH2YK FB-AK, HN-ME, NP-NT	*	*	19.2km, 240°
JORUM	BOXCAR	2.0km, 168°	PG-BC, RK-ON, WH2YK HN-ME, SV3QB, NP-NT	29.0km, 151°	8.3km, 206°	34.4km, 30°
JORUM	BOXCAR	2.0km, 168°	PG-BC, RK-ON, WH2YK HN-ME, SV3QB, NP-NT LC-NM	80.5km, 32°	25.7km, 12°	10.6km, 60°
FAULTLESS	BOXCAR	150.2km, 188°	PG-BC, RK-ON, WH2YK HN-ME, SV3QB, NP-NT	29.0km, 151°	14.8km, 358°	26.0km, 36°
FAULTLESS	BOXCAR	150.2km, 188°	PG-BC, RK-ON, WH2YK HN-ME, SV3QB, NP-NT LC-NM	80.5km, 32°	23.3km, 5°	8.6km, 130°
MILROW	LONG SHOT	2.4km, 178°	WH2YK, NP-NT, PG2BC, KN-UT, RK-ON, CR2NB, SJ-TX, HN-ME, BE-FL	22.8km, 26°	5.0km, 186°	60.8km, 68°

*No arrival times for JORUM COLLAPSE could be determined since gains had not been increased at this time (about four hours) after JORUM explosion.

Ordinarily the increased aperture would improve the body-wave and relative travel-time locations, but the poor agreement of travel time to LC-NM from the source area with the Herrin 1968 tables and the possibility that LC-NM lies near a crossover in the travel-time curve overrides the aperture factor. It is significant that the matched filter location with LC-NM added is comparable in accuracy to the relative travel-time location without LC-NM for JORUM-BOXCAR and FAULTLESS-BOXCAR because in practice the matched filter method can always use regional data while the other method usually cannot.

The extremely large error in the matched filter location of LONG SHOT compared to the relative travel-time location prompted a search for causes of error in the new method. It was found that digitization rates for the MILROW and LONG SHOT records were imprecise, up to five seconds of real time, either way, over the duration of the signals. This would cause correlation peak times to be inaccurate. Also, we must recognize that the poor signal-to-noise ratio of some LONG SHOT recordings could cause correlation peak times to be somewhat in error. These reasons would account for much of the 61 km displacement of the computed LONG SHOT location from its true epicenter.

An attempt was made to utilize the phase differences method as discussed above for the FAULTLESS-BOXCAR event pair. The cross correlation traces were truncated about the peak used to make the matched filter location, and the Tukey (Hanning) time window was applied. The length of the truncated correlation trace was about 100 seconds for all seven stations. Computed amplitude and phase spectra were fairly smooth. However, only three stations produced dispersion curves based on the phase spectra which were realistic. Inverse dispersion resulted at two stations. No location was calculated with these intractable

results. The method of determining phase velocity was checked with synthetic cases. It was found that phase velocity curves used to construct synthetic seismograms at various distances can be precisely extracted from the cross correlations of these seismograms with dispersed modifications of themselves. Three factors may have induced failure of four of the FAULTLESS-BOXCAR cross correlations to produce realistic phase velocity curves: 1) signals recorded at these stations were of relatively short duration and limited bandwidth; 2) even though the epicenters were only 150 km apart, the travel paths were sufficiently different to produce dissimilar dispersion effects; and 3) there may have been interference from refracted energy arrivals.

SUMMARY AND DISSCUSSION

A method of relative seismic event location using surface waves has been developed which is analogous to relative travel-time locations obtained using short-period body waves. Sources of error in this method are: 1) differences between assumed and true phase velocities in the source region and along travel paths, 2) dispersion of one signal relative to the other at a given station, 3) background noise superimposed on actual surface-wave recordings, and 4) imprecise digitization rates. It was shown that the first should be negligible with only the grossest knowledge of the structure in the source region and along travel paths. The second should be reduced by a refinement of the method; i.e., Fourier analysis of the cross correlation trace. However, this refinement may be practical only in certain cases. The third is always troublesome, but some noise could be suppressed by band-pass filtering and beamforming in arrays. Since explosions generate Rayleigh waves which have a much higher detection threshold than body waves from the same event, the matched filter location method cannot be applied in many cases where body waves from an event have distinct first arrivals and a computed location using them is reliable. Unless background noise on long-period instruments is substantially reduced, the matched-filter method cannot compete with the relative travel-time method for smaller events. The fourth cause of error is a hardware problem, but precise digitization rates are certainly possible.

Matched filtering could be conducted by analog or digital techniques on-line in several observatories assigned to monitor one or more areas. Immediately upon a confirmed detection by the reference event matched filters, a location could be computed using the relative "travel-times" of the Rayleigh

waves. A sophisticated application of this new technique could produce a location as rapidly and perhaps as precisely as the short-period relative travel-time method. Furthermore, it may be possible to discriminate earthquakes from explosions in a given region when using reference signals known to be produced by an explosion. This follows from the fact that earthquakes have azimuthally-dependent phase radiation patterns as illustrated by Ben Menahem and Harkrider (1964). Not only would location accuracy be severely impaired by the earthquake's phase radiation pattern, but also the time residuals after the final iteration in the matched filter location could be as much as one-half cycle of the periods of maximum recorded amplitude since initial phases at the source may be separated by 180°. In this study, the final residuals for all stations for all surface-wave locations except MILROW-LONG SHOT were less than 3.6 seconds. Imprecise digitization rates account for much of this, and residuals were higher for the MILROW-LONG SHOT pair because of more imprecise digitization errors compounded with the longer duration of the signals.

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY ADVANCED RESEARCH PROJECTS AGENCY NUCLEAR MONITORING RESEARCH OFFICE WASHINGTON, D. C.

13. ABSTRACT

A method of relative location for explosions using Rayleigh waves is developed and tested. It involves cross correlating a wavetrain with a previously recorded signal from the same source region and determining a relative "travel-time" from the peak in the cross correlation trace. Locations are fairly accurate, but do not compare with the precision obtained with body waves and relative travel-time corrections. A number of causes of errors are discussed, and it is estimated that a sophisticated application of this method would yield location comparable to relative travel-time locations for large events. ( )

14. KEY WORDS

Epicenter location
Matched filter
Relative Travel-Time Anomalies

Unclassified
Security Classification